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Radar Detection of Lightning and Electric Fields

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ATMOSPHERIC SCIENCES DIVISION PROJECT 2310
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13. ABSTRACT *(Maximum 200 words)*
In recent years, there has been increased interest in the use of radars to identify electrified clouds and to quantify electrification processes. This report surveys the use of radars to observe lightning and to observe the effects of electric fields on the orientations of hydrometeors. Observations of lightning channels, conducted with increasing sophistication since the 1940's, have revealed the wavelength dependence of the reflectivity of lightning, the distribution of lightning echoes in storms, and the differential reflectivity of lightning. Observations of electrified clouds with polarization diversity radars during the 1970's and early 1980's revealed changes of orientations of ice crystals due to varying electric fields. These techniques can now be used in coordination with measurements of electric fields and radio-frequency emissions from lightning discharges to gain valuable new knowledge of the structure and evolution of electric fields in clouds. This report suggests several approaches to the continued investigation of electrical processes in clouds by radars.

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1. INTRODUCTION

Ever since meteorological radars were first used in the 1940's, they have proven to be invaluable for investigating the internal structure and dynamics of convective storms. The capability of measuring reflectivity and Doppler mean velocity as functions of azimuth, elevation, and range has greatly increased understanding of storm morphology and kinematics and precipitation formation. Because of the relations of electrical processes to cloud microphysical processes, it seems reasonable to expect that radars can also yield information concerning electrical processes in storms. This use of radars has proven difficult, primarily because of the intermittency and short time scales of electrical phenomena. However, certain electrical phenomena can be identified and, to some extent, quantified by radar measurements. These include the ionized channels of electrical discharges within clouds and the orientations of ice crystals and raindrops influenced by electric fields in clouds. In the following sections we review past measurements of electrical phenomena by radar, discuss the difficulties and uncertainties associated

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with the various types of measurements, and identify opportunities for advancement of knowledge.

The use of radars to study lightning was reviewed recently in detail by Williams et al.[1] Therefore we discuss this topic only briefly here and focus primarily on electric fields and the extent to which their effects are detectable by radar.

2. DETECTION OF LIGHTNING CHANNELS

2.1. Natural Lightning

The earliest observation of lightning by radar, described by Ligda,[2] occurred in Panama during the 1940's. The technique was based on observation of a radar A-scope, an oscilloscope that displays the echo intensity as a function of range. The radar beam was directed toward a storm and then elevated until the A-scope display was about halfway to saturation; echoes from lightning then could be observed as momentary enhancements of echo power superimposed on the echo from precipitation. Subsequently Ligda[3] described a photographic technique whereby lightning echoes detected by radar could be discriminated from precipitation echoes. This technique was used by Atlas[4] to depict lightning echoes observed with an FPS-6 radar of 10.7 cm wavelength (Figure 1). This radar, a height-finder with a vertical beamwidth of 0.9° and horizontal beamwidth of 3.0°, scanned a vertical sector of 30° at a rate of 2.9 sec per scan cycle (up and down). On the basis of reports by a cooperative observer, Atlas estimated that about 42% of lightning discharges were detected. He further estimated that the duration of the lightning echoes was 0.1–0.5 sec, which typically permitted detection of the full height of a lightning channel in this mode of radar operation, since the radar scanned the full height of the storm at the observed range of about 200 km in about 0.2 sec.

More recent observations of lightning by radar have been made with techniques similar in concept to that described by Ligda.[2] More

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(Due to the large number of references cited above, they are not listed here. See References, page 25.)

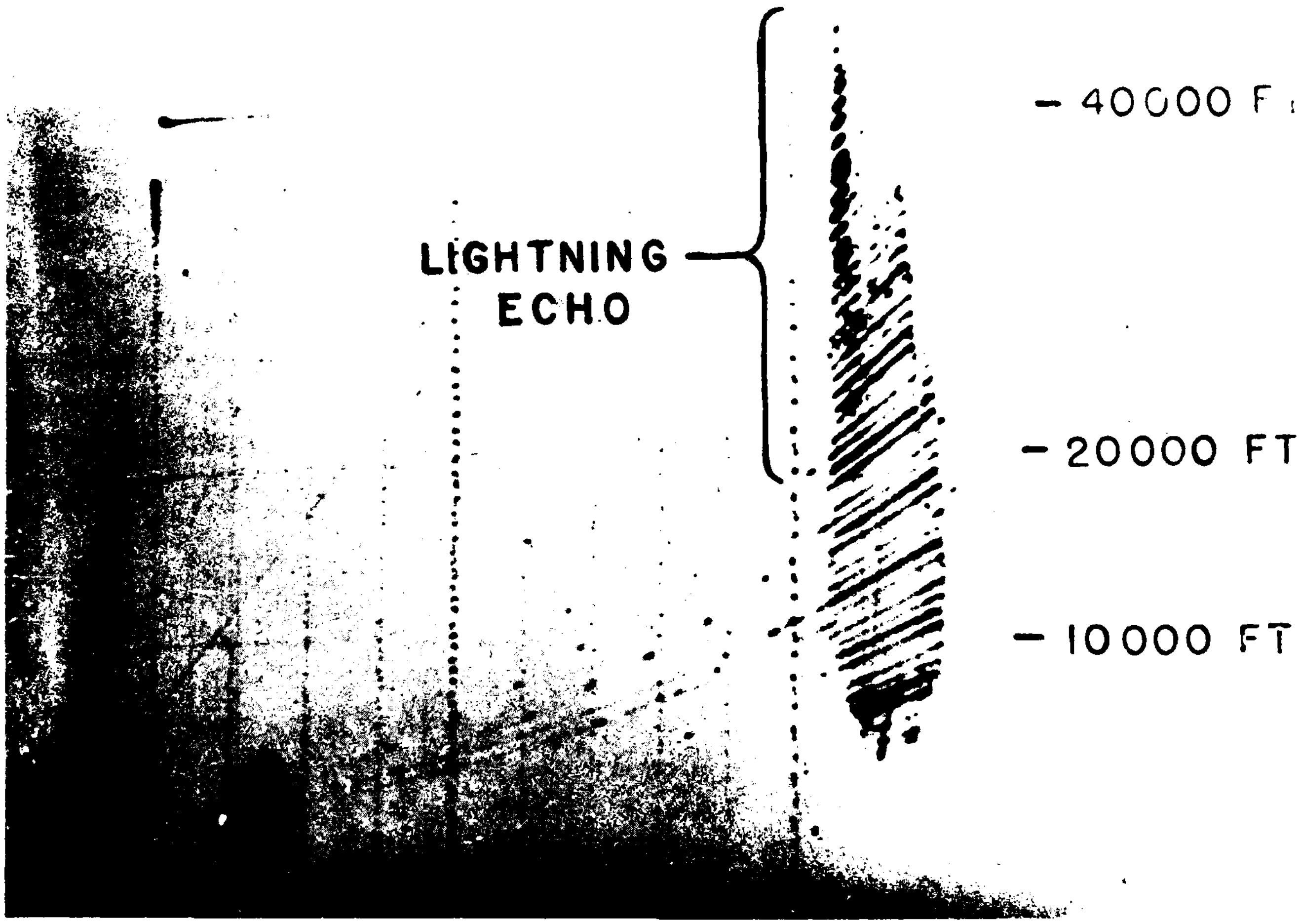

Figure 1. Lightning Detected by Scanning Radar. Lightning echo extends upward from a thunderstorm observed in elevation scan by 10.6 cm FPS-6 radar in S. Truro, Mass. (Copyright 1959 by Pergamon Press, reprinted with permission).[4]

sophistication has been introduced in that the electrical activity can be identified by lightning detection networks and the detection criteria are more quantitative. Observations with radars of 10–11 cm wavelength show that lightning echoes typically have an equivalent reflectivity factor (Z_e) of 35–40 dBZ (Figure 2).[5] Because the lightning channel appears as a relatively coherent, or "hard," target with a persistence time of a few tenths of a second, it is easy to discriminate it from the precipitation echo observed at a fixed antenna position. It is more difficult to detect lightning echoes if the antenna is scanning, partly because of the spatial variability of the precipitation echo and partly because of the intermittency of the discharges.

Comparative observations by radars of 5, 11 and 68 cm wavelengths[6, 7] suggest that the reflectivity (cross-section per unit volume) of lightning echoes is approximately proportional to the inverse square of the wavelength, but the wide range of reflectivities observed makes it difficult to specify a more precise relationship. However, the intensity of lightning echoes is much less sensitive to wavelength than is that of precipitation echoes, which is proportional to the inverse fourth power of wavelength. Thus, lightning echoes are detectable only in regions where the reflectivity factor due to hydrometeors is less than about 30 dBZ at 10 cm wavelength and about 20 dBZ at 5 cm wavelength. At longer wavelengths, on the other hand, detection of lightning is possible throughout the core of a severe thunderstorm. In a series of measurements at Wallops Island, Va., in 1982 and 1983 hydrometeor reflectivity was observed with a radar of 10 cm wavelength and lightning echoes were observed with a radar of 70.5 cm wavelength (Figure 3).[8, 9] In these measurements, the 70.5 cm radar was pointed along the azimuth of the storm core and stepped in elevation by 2° increments, dwelling about 15–30 sec at each elevation.

The foregoing discussion pertains to detection by radars that transmit a signal of fixed linear polarization and receive a signal of identical polarization, i.e., the "copolarized" backscattered signal. This is the mode of operation of most weather surveillance radars. Detection of lightning echoes by radars of shorter wavelengths, e.g., 3 cm, is possible through reception of the cross-polarized backscattered signal with a dual-channel receiver. The ionized lightning channel generates a cross-polarized backscattered signal that is typically much larger than the cross-polarized signal generated by hydrometeors. Radars transmitting circularly polarized

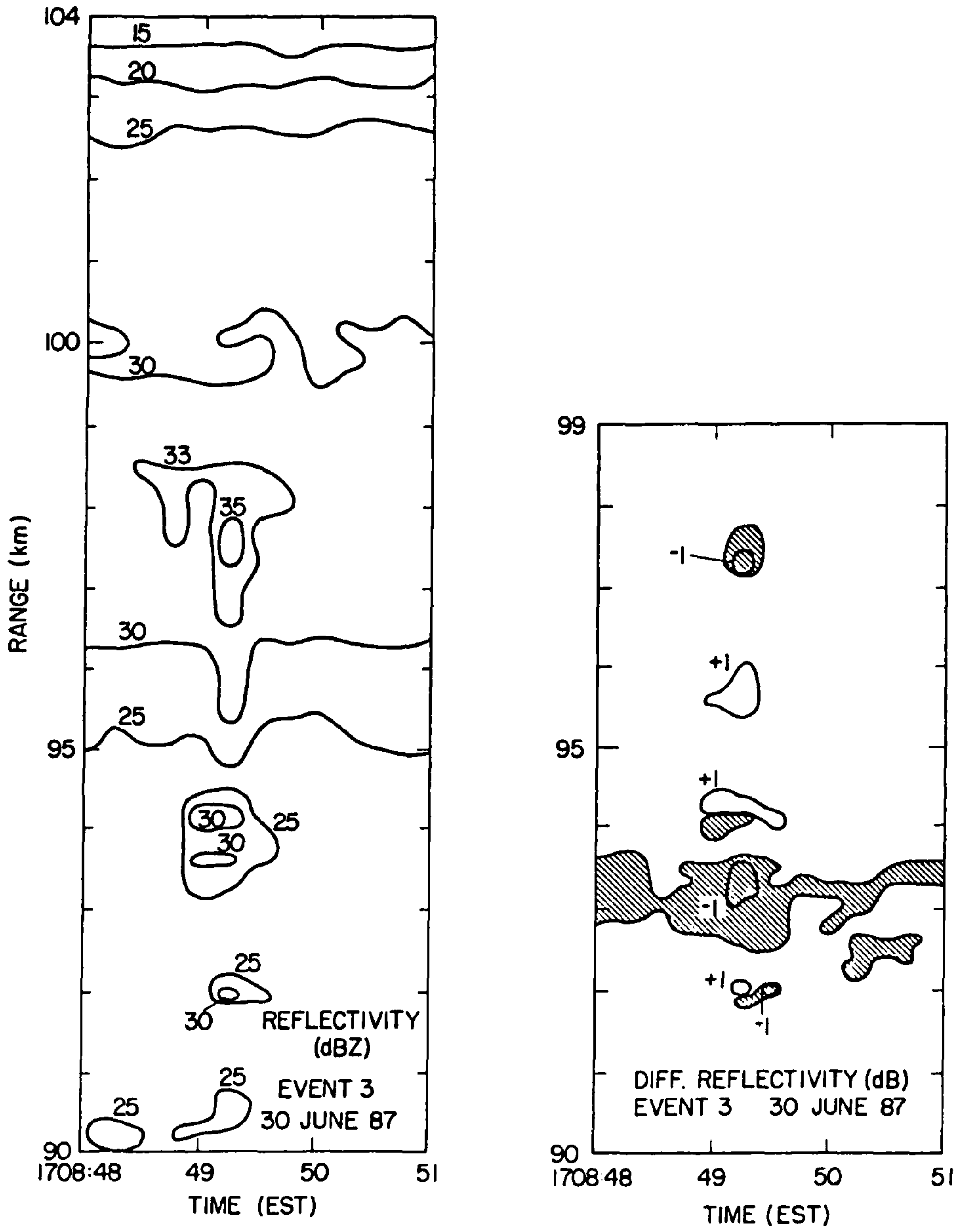

Figure 2. Lightning Detected by 11 cm Radar with Fixed Beam. Lightning echo observed above a core of high reflectivity by 11 cm radar at the Geophysics Laboratory. *Left panel:* Equivalent reflectivity of lightning channel exceeds 35 dBZ and is as much as 4 dB above the reflectivity due to hydrometeors. *Right panel:* Differential reflectivity reveals distinct regions of positive and negative values, indicating respective tendencies toward horizontal and vertical orientations of channels.

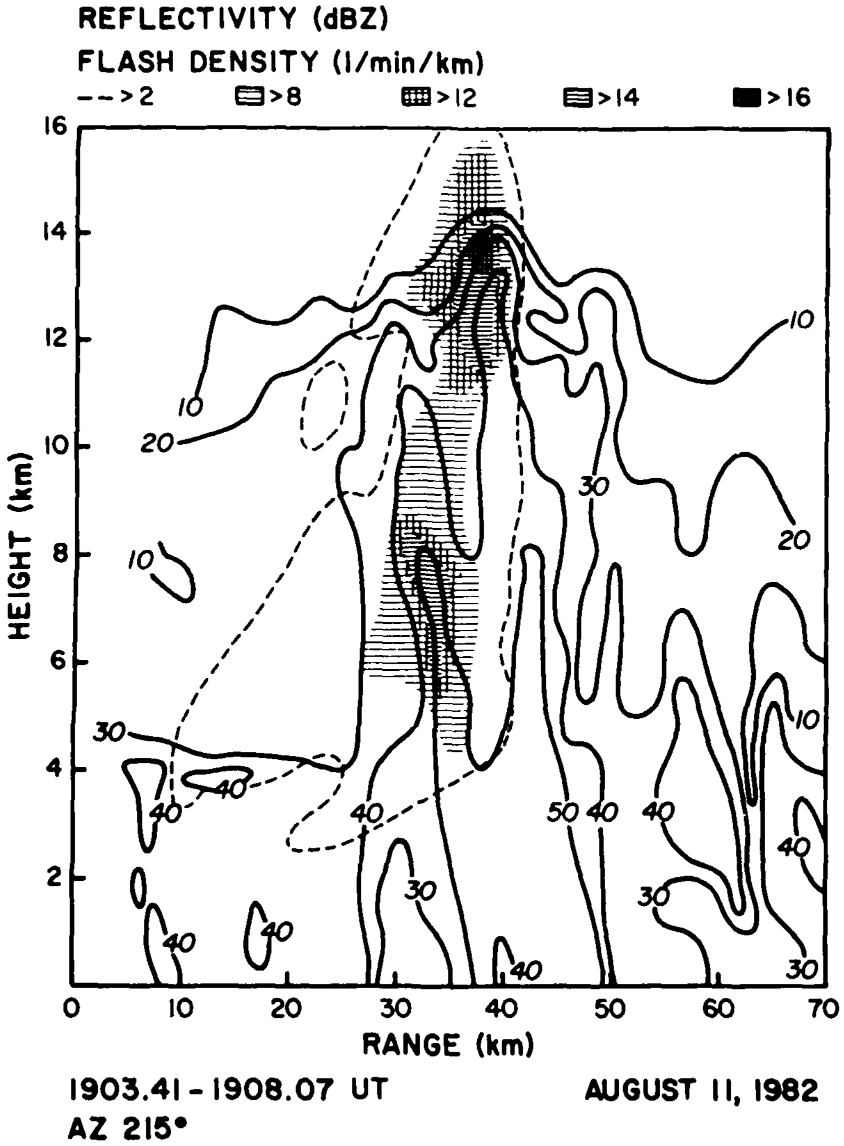

Figure 3. Lightning Detected by 70.5 cm Radar. Lightning flash density was measured at Wallops Island, Va., with radar beam held fixed at successive heights in a thunderstorm. Reflectivity factor (Z) was measured by a co-located 10 cm radar scanning in elevation angle (Copyright 1984 by the American Geophysical Union, reprinted with permission).[8]

signals receive a backscattered signal from hydrometeors that is predominantly of *opposite* polarization to that of the transmitted signal. In this case, therefore, the backscattered signal from lightning channels is most evident in the received signal of polarization *identical* to that of the transmitted signal. An observation of this type was made with the 1.8 cm (K_u-band) polarization diversity radar of the National Research Council of Canada in Ottawa[10] but was never published. Similar observations, also unpublished, were made with the 10 cm (S-band) polarization diversity radar of the Alberta Research Council in Penhold, Alberta.[11] In all these cases, the lightning echo was described as strongly depolarized, although no quantitative measurements were recorded. Analogous observations have been made recently with a 3 cm (X-band) linearly polarized dual-channel radar at the New Mexico Institute of Mining and Technology (NMIMT).[12]

Dual-channel receivers not only facilitate the detection of lightning echoes in moderate or greater precipitation by radars of 11 cm or shorter wavelength but also may permit the measurement of the orientation of lightning channel segments within the radar beam. This could be done by means of the techniques described by McCormick and Hendry[13] and used by them to measure orientations of hydrometeors. These techniques have never been applied to the study of lightning channels. Another approach to the measurement of the orientation of lightning channel elements is the use of the polarization differential reflectivity, which is the ratio of the respective copolarized backscattered powers due to transmitted signals of horizontal and vertical polarization. This quantity reveals any tendency for the channels to be horizontally or vertically oriented. Such measurements have been made at the Geophysics Laboratory (Figure 2).[5]

2.2. Triggered Lightning

An electric discharge can be triggered if an aircraft is in or near an electrified cloud, because of the electrostatic charge on the aircraft or the perturbation of the ambient electric field. This type of lightning, which has also struck spacecraft during launch, can occur even if the electric field in and around the cloud is too weak to cause natural lightning. The use of a ground-based radar to observe lightning triggered by an aircraft requires

precise tracking of the aircraft, and consequently such observations are rare. Mazur et al.[14, 15] used the 70.5 cm radar at Wallops Island, Va., to observe lightning triggered by the F-106B research aircraft operated by the National Aeronautics and Space Administration. The radar data, with a time resolution of 30–40 msec, show discharges originating at the aircraft and propagating outward.

Lightning triggered intentionally by rockets trailing wires has been used to measure currents and other attributes of lightning. Rocket-triggered discharges should provide relatively well documented targets for radar measurements. Measurements of triggered lightning with a 5.4 cm radar[16] were made with the objective of identifying correlated effects on precipitation, i.e., verifying the hypothesized "rain gush" phenomenon. Multiple-wavelength radar observations of triggered lightning have been proposed but never made.

3. DETECTION OF ELECTRIC FIELD EFFECTS

3.1. Theory of Dual-channel Radar Measurements

This subsection summarizes the theory associated with the use of polarization diversity radars to observe the effects of electric fields on the orientations of hydrometeors in clouds. Examples of these observations are shown in subsections 3.2 and 3.3. The casual reader may gain a general appreciation of the variety of measurement techniques and results from the following subsections without reading the present subsection in detail. However, some understanding of the theory is necessary for a deeper appreciation of the wealth of information that is revealed by these measurements.

The estimation of shapes and orientations of hydrometeors by radar requires, at minimum, the transmission of either a circularly polarized signal or alternating orthogonal linearly polarized signals and the simultaneous reception of two signals of orthogonal polarizations. Because most of the pertinent measurements have been made with circular polarization, the following discussion is limited to this option. The radar

measurement comprises, at minimum, the signal amplitude in each of two receiver channels and the relative phase of the two signals. From these one can derive the received power in each channel, i.e., the autocovariances of the respective signals, and the complex cross-covariance of the two received signals. The following formulation is based substantially on that of McCormick and Hendry.[13]

The signal received in the channel orthogonal to the channel of transmission, which is sometimes called the "main" signal, is given by

$$E_2 = \sum_n E_{2n} = \sum_n \sigma_n^{1/2} \exp(-i\, 2kr_n) \,/\, (2r_n^{\,2}), \tag{1}$$

and the signal received in the channel of transmission is given by

$$\begin{aligned} E_1 &= \sum_n E_{1n} \\ &= \sum_n \frac{\sigma_n^{1/2} \{\nu_n \exp[i\,(\delta_n \pm 2\alpha_n)] + 2p \exp[i\,(\chi \pm 2\tau)]\} \exp(-i\, 2kr_n)}{2r_n^{\,2}}. \end{aligned} \tag{2}$$

Here σ_n is the backscatter cross-section for a single scatterer at range r_n (defined for the "main" component of backscatter, which is in channel 2), and k is the propagation constant in free space. The ratio of the backscattered amplitudes, ν_n, is an increasing function of the ellipticity of the scatterer. The backscatter phase shift, δ_n, is near $-\pi$ radians ($-180°$) for small (Rayleigh-Gans) oblate spheroidal scatterers with vertically oriented axes of symmetry but varies for larger scatterers. The total phase shift due to a non-spherical scatterer is modified by its apparent canting angle, α_n. The propagation term, $2p \exp[i\,(\chi \pm 2\tau)]$, describes the depolarization of a circularly polarized signal in a medium filled with non-spherical particles. As formulated by McCormick and Hendry,[13] it is based on a model of an anisotropic medium with principal axes rotated through an angle τ from the vertical and horizontal. The parameters p and χ are related to the total one-way differential attenuation, ΔA (dB), and differential phase shift, $\Delta\Phi$ (deg), relative to the principal axes of the propagation medium, to first-order approximation by

$$p(d) \exp[i\, \chi(d)] = \tanh[\,0.0575\, \Delta A(d) + i\,(\pi/360)\, \Delta\Phi(d)], \tag{3}$$

where d is the path length. The differential attenuation and differential phase shift are defined to be positive if the attenuation and phase shift, respectively, are greater for horizontally polarized signals than for vertically polarized. (This is the typical condition in rain.) The upper and lower signs in the foregoing equations correspond to the transmission of right and left circular polarization, respectively. *Thus the signal received in the channel of transmission, E_1, is related to the ellipticity of the scatterers in the volume sampled by the radar and to the anisotropy of the propagation medium.*

When the complex products of these signals are averaged, the terms with unlike indices vanish, so that the expected values of the autocovariances are given by

$$R_1 = \langle E_1 E_1^* \rangle = \sum_n \frac{\sigma_n \, | \nu_n \exp[i(\delta_n \pm 2\alpha_n)] + 2p \exp[i(\chi \pm 2\tau)] |^2}{4 r_n^4} \qquad (4)$$

and

$$R_2 = \langle E_2 E_2^* \rangle = \sum_n \sigma_n / (4 r_n^4), \qquad (5)$$

and the expected value of the cross-covariance is given by

$$R_{12} = \langle E_1 E_2^* \rangle = \sum_n \frac{\sigma_n \{ \nu_n \exp[i(\delta_n \pm 2\alpha_n)] + 2p \exp[i(\chi \pm 2\tau)] \}}{4 r_n^4}. \qquad (6)$$

Finally, the summations can be replaced by integrals incorporating the drop size distribution and a sample volume proportional to the square of the range.

The absolute reflectivity is derived from the received power R_2 in the channel opposite to the channel of transmission, as described above. The ratio of the two powers, the circular depolarization ratio,

$$CDR = R_1 / R_2, \qquad (7)$$

is a power-weighted (reflectivity-weighted) average of the quantity $| \nu_n \exp[i(\delta_n \pm 2\alpha_n)] + 2p \exp[i(\chi \pm 2\tau)] |^2$. It is a joint measure of the *degree of ellipticity of the particles* in the volume sampled by the radar and of the *anisotropy of the propagation path.* Note that the particles in the sample volume need not have a common orientation to contribute to R_1.

From the cross-covariance one can derive the cross-correlation,

$$\rho \exp(i\phi) = R_{12} / (R_1 R_2)^{1/2}. \tag{8}$$

If propagation effects are negligible, the magnitude of this quantity, ρ, provides an estimate of the degree of common orientation of the hydrometeors in the backscattering volume, and from its angular argument, ϕ, one can derive an estimate of the average orientation angle, or mean apparent canting angle. The cross-correlation is more difficult to interpret when propagation effects are present. In this case, it is more useful to examine the cross-covariance amplitude ratio,

$$\mathrm{CCAR} = R_{12} / R_2. \tag{9}$$

This ratio is a power-weighted average of the quantity $\{\nu_n \exp[i(\delta_n \pm 2\alpha_n)] + 2p \exp[i(\chi \pm 2\tau)]\}$. It is convenient to express this quantity in the form

$$\mathrm{CCAR} = \rho_\alpha \bar{\nu} \exp[i(\bar{\delta} \pm 2\bar{\alpha})] + 2p \exp[i(\chi \pm 2\tau)], \tag{10}$$

where $\bar{\nu} \exp(i\bar{\delta})$ is the reflectivity-weighted mean value of $\nu_n \exp(i\delta_n)$, $\bar{\alpha}$ is the mean apparent canting angle, and ρ_α is the effective fraction of scatterers having a common orientation. The latter quantity can be expressed by $\rho_\alpha = \exp(-2\sigma_\alpha^2)$, where σ_α is the standard deviation of a Gaussian distribution of apparent canting angles. The CCAR is of particular interest because it is a sum of two terms, one due to backscattering effects and one due to propagation effects. Note that *only the scatterers having a common orientation contribute to the backscattering term of the CCAR.* When the symmetry axes of the propagation medium are horizontal and vertical, the real part of the propagation term is proportional to the differential attenuation and the imaginary part is proportional to the differential phase shift, as implied by Equation (3). Rangewise increments of the real and imaginary parts yield estimates of the incremental rates of differential attenuation and differential phase shift. Examples discussed in subsection 3.3 show that the CCAR reveals these characteristics readily when it is plotted as a function of range in the complex plane.

Electrical effects are most evident in the degree of common orientation, ρ_α, deduced from the cross-correlation, and in the angular quantities $\bar{\alpha}$ and τ, because of the tendency of hydrometeors to become aligned by an electric field. It has been suggested[10] that *only* small ice crystals will reveal rapid changes of the electric field, because of their small moments of inertia. The following subsections include examples of radar measurements, descriptions of the pertinent physical mechanisms, and discussion of the merits of particular wavelengths or observational modes for investigating the electrical structure of clouds. While the following subsections emphasize backscatter and propagation effects respectively, it should be emphasized that the two categories of effects are likely to be combined in any measurement, especially at shorter wavelengths, so that they cannot be treated separately unless one of them is dominant.

3.2. Backscatter Effects

Polarization diversity radars, i.e., differential reflectivity radars or dual-receiver radars, can be used to detect the effects of electric fields on ice crystals or water drops in clouds. Most easily detected are changes in the orientation of ice crystals due to changes in electric fields. These effects were first reported by McCormick and Hendry[17] by means of the techniques described in subsection 3.1. They have been investigated theoretically by Weinheimer and Few.[18] Published observations have all been made with the radar antenna held in fixed position. These have revealed cyclical changes in orientations of hydrometeors between highly oriented and more randomly oriented states, as shown in Figures 4 and 5, apparently due to repeated charging and discharging within the clouds. A similar observation was made in 1975 by Brook[19] at NMIMT (Figure 6); using a 3 cm linearly polarized dual-channel radar, he observed a sharp increase in the cross-polarized backscatter coincident with a lightning stroke that was not detected by the radar. (This radar was damaged by lightning after a brief period of operation and was not restored to service until 1989.) Such observations have never been made in conjunction with detailed documentation of electric fields or discharges in the clouds.

In the past few years, attempts have been made to identify effects of

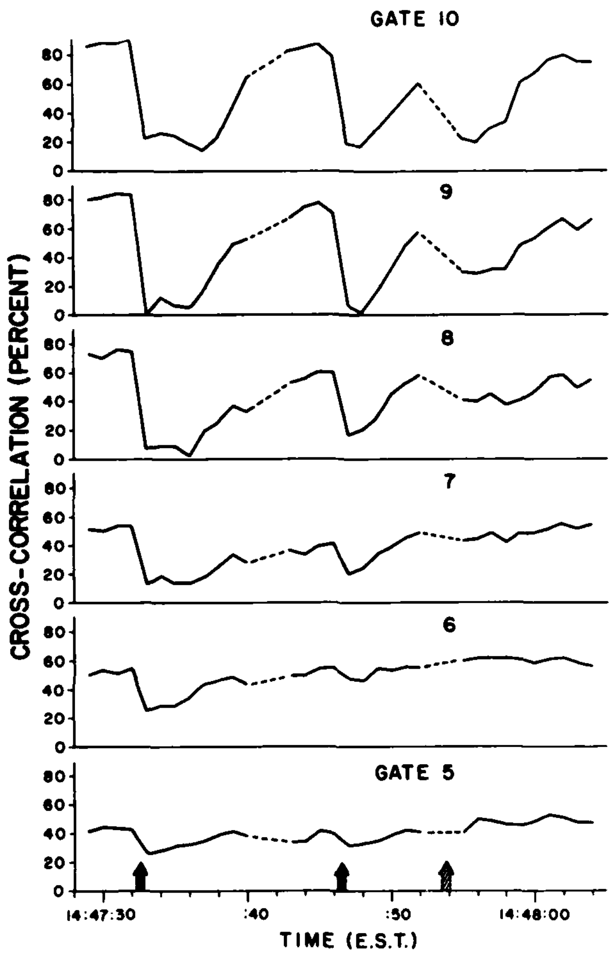

Figure 4. Effect of Electric Field on Orientation of Ice Crystals, 1. Observation was made in 1974 by 1.8 cm radar at the National Research Council of Canada in Ottawa. Range gate spacing is 0.5 km beginning at 15.4 km (Gate 5), elevation angle is 30.3°, and height is 7.8–9.0 km. Cross-correlation of right and left circularly polarized signals implies gradually increasing degree of orientation with increasing electric field and rapid change to random orientation as field is discharged (after McCormick and Hendry, 1976).[17]

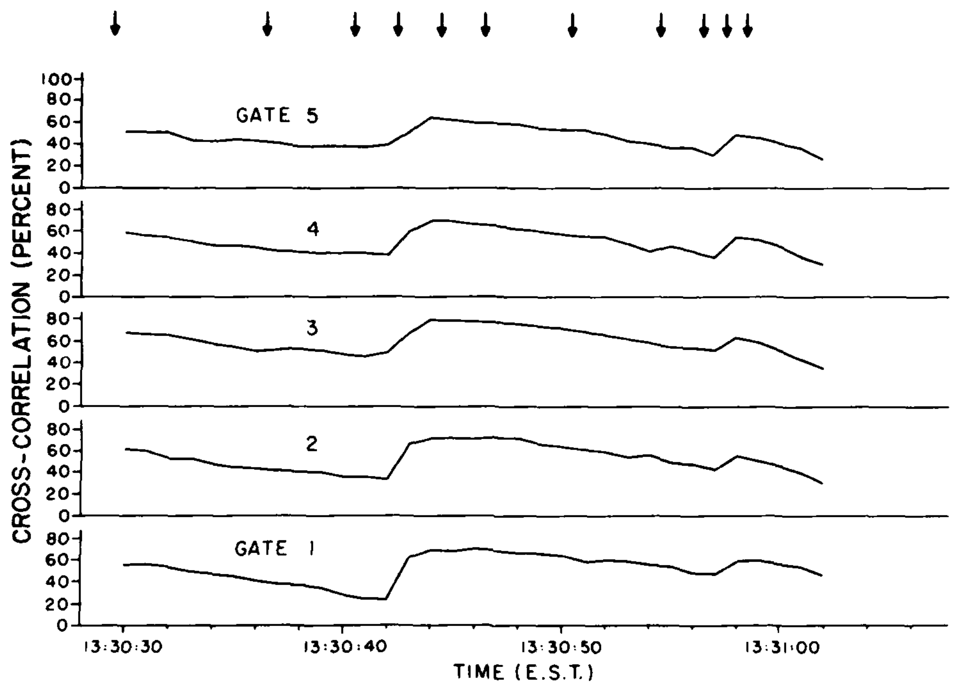

Figure 5. Effect of Electric Field on Orientation of Ice Crystals, 2. Observation was made in 1975 by 1.8 cm radar at the National Research Council of Canada in Ottawa. Range gate spacing is 0.5 km beginning at 16 km, elevation angle is 21.3°, and height is 5.8–6.5 km. Cross-correlation of right and left circularly polarized signals implies gradually decreasing degree of orientation with increasing electric field and rapid change to higher degree of orientation as field is discharged (Copyright 1976 by American Geophysical Union, reprinted with permission).[29]

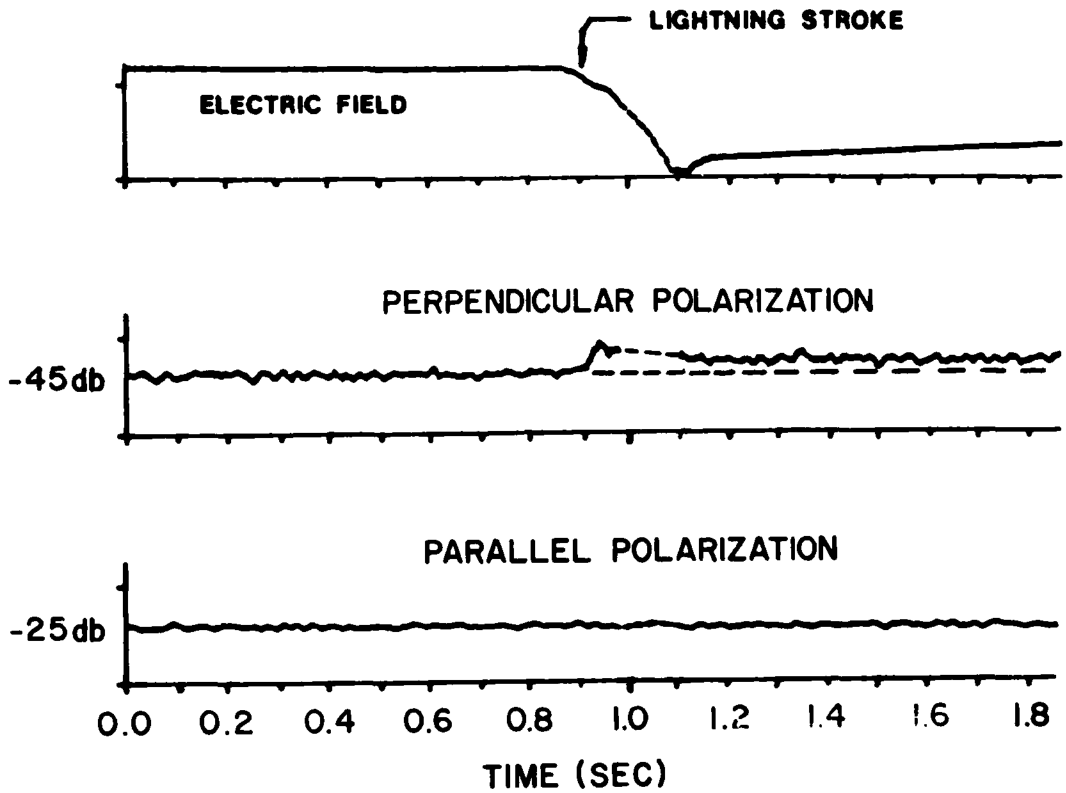

Figure 6. Effect of Electric Field on Orientation of Ice Crystals, 3. Observation of linear copolarized and cross-polarized backscatter was made in 1975 in Socorro, N. M., by a 3.1 cm radar. Elevation angle is 67.9°, and height is 10.7 km above ground level. *Top panel:* Electric field at the surface, recorded near the radar, is sharply reduced following lightning stroke. *Center panel:* Linear cross-polarized backscatter power increases by about 1 dB in an interval of less than 0.1 sec coincident with the lightning stroke. Persistence of the increased signal for nearly 1 sec implies that it is due to a change of orientations or apparent shapes of hydrometeors, which are probably ice crystals, and not to the lightning channel. *Bottom panel:* Linear copolarized backscatter power shows no effect of lightning (Courtesy of M. Brook and P. Krehbiel, New Mexico Institute of Mining and Technology).

lightning on falling hydrometeors, e.g., enhanced coalescence leading to larger raindrops, by means of a Doppler radar with a single fixed polarization.[16, 20, 21, 22, 23] Attempts to measure changes in reflectivity or Doppler velocity of precipitation due to lightning[16, 22] yielded generally negative results, i.e., no systematic variation of either the reflectivity or the Doppler spectrum in conjunction with lightning. Observations of Doppler spectra at vertical incidence by Zrnic et al.[21] revealed an apparent momentary decrease of hydrometeor reflectivity within a few tenths of a second following a lightning discharge. This was observed at 10 km altitude in a region of reflectivity near 20 dBZ. They speculated that the decrease was due to a temporary realignment of ice crystals in conjunction with the lightning discharge. Recent attempts with radars of 10–11 cm wavelength to discern changes of differential reflectivity coincident with lightning discharges, both at the National Severe Storms Laboratory[24] and at the Geophysics Laboratory, have been unsuccessful.

There are several possible reasons for this lack of success. First, these attempts mostly involved scanning large domains of elevation angle. If an electrically active region is of small spatial extent, a narrow-beam radar scanning the full height of the storm at short range is likely to miss any particular lightning event. On the other hand, there is ample evidence that lightning discharges may extend several kilometers both horizontally and vertically, so that perturbations of the electric field should be similarly widespread. Detection of reorientation of the hydrometeors by changes of the electric field may be successful if the elevation scan is limited to a few degrees and a scan cycle time of a few seconds. Second, the differential reflectivity is probably not the optimum quantity in which to detect the effects of electric fields. The relationship between the differential reflectivity and the mean apparent canting angle, $\bar{\alpha}$, and degree of orientation of the hydrometeors, ρ_{α}, is not simple, and the fact that the effects of electric fields have been observed in the latter quantities does not guarantee that they can be detected in the differential reflectivity. Very recently Krehbiel,[12] using the restored 3 cm radar at NMIMT, observed temporal variations in the linear depolarization ratio of backscatter from hydrometeors near 10 km altitude in a small convective storm coincident with lightning events detected in the cross-polarized channel of the radar receiver (Figure 7).

All the measurements and most of the attempted measurements cited

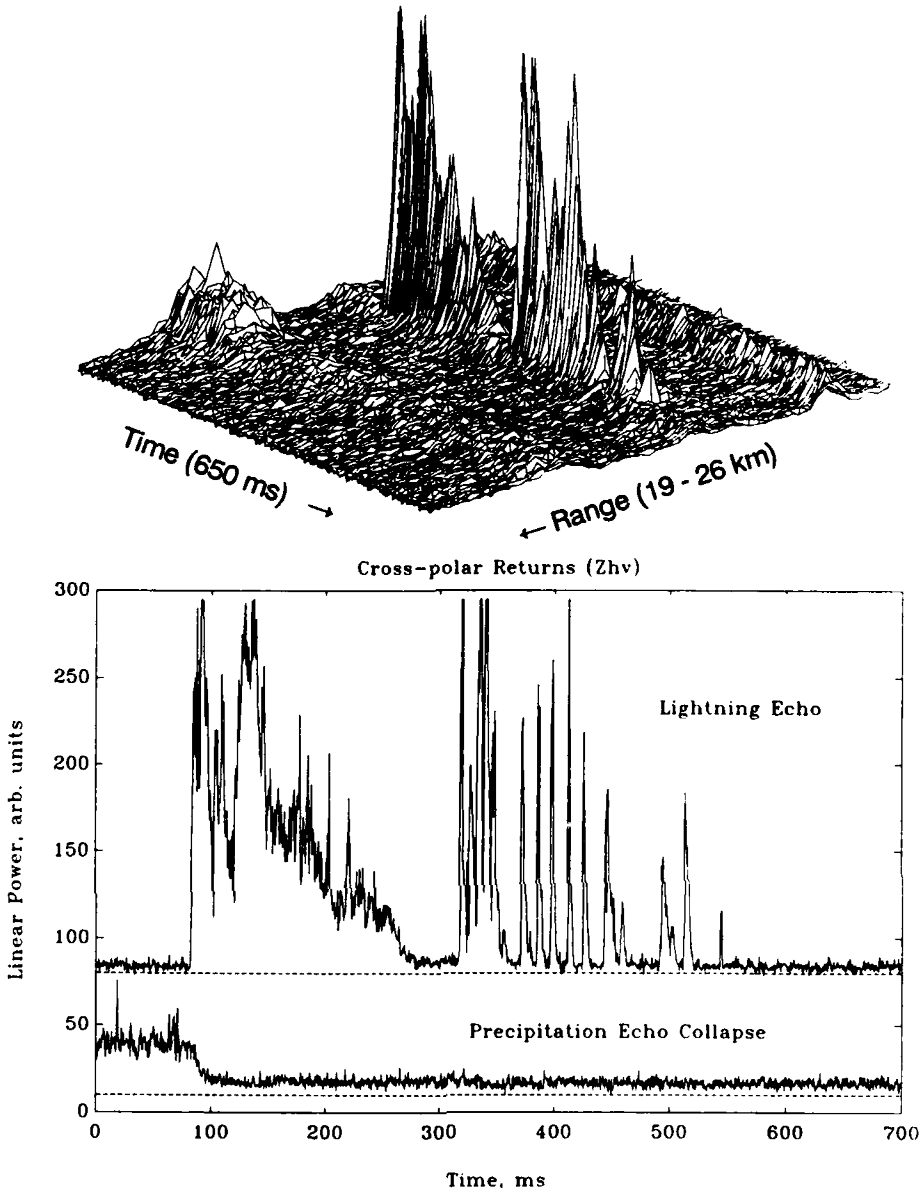

Figure 7. Radar Observation of Simultaneous Lightning and Reorientation of Hydrometeors. Observation of linear cross-polarized backscatter power was made in 1989 in Socorro, N. M., by a 3.1 cm radar. *Upper panel:* Power (vertical coordinate) as a function of time and range shows hydrometeor echo near 24 km range and lightning echo near 22 km range. *Lower panel:* Power from lightning and hydrometeors as functions of time at 22 and 24 km range, respectively, show that decrease of backscatter from hydrometeors is nearly simultaneous with initiation of lightning echo. Decrease of cross-polarized backscatter power from hydrometeors is probably due to increased randomness of orientation as local electric field is suddenly decreased (Courtesy of P. Krehbiel, New Mexico Institute of Mining and Technology).[12]

above involved the effects of electric fields on ice crystals. The effect of electric fields on water drops has been demonstrated in laboratory experiments[25] and described by calculations from theory.[26, 27] These results show that an increasing vertical electric field progressively distorts a water drop from its oblate spheroidal equilibrium shape. In particular, a field of 1 MV m^{-1} distorts an uncharged water drop of equivalent spherical radius 2.3 mm so as to yield a "tear-drop" shape. (This field strength is approximately sufficient for dielectric breakdown of air containing water drops of 1-mm radius.[28]) If such a field is rapidly decreased by a lightning discharge, the effect on water drops should be measurable in either the linear polarization differential reflectivity, the circular depolarization ratio, or the cross-correlation of orthogonal circularly polarized signals.

3.3. Propagation Effects

Temporal variations in electric fields affect the shapes and orientations of hydrometeors not only in a backscattering volume at a particular range but also in the path between the radar and that range. The resulting anisotropy of the propagation medium can produce significant depolarization of a circularly polarized radar signal, due to differential attenuation and differential phase shift, and can dominate any depolarization due to backscatter, particularly at wavelengths of a few centimeters or less. Electrical effects on the propagation parameters are strongly dependent on the radar wavelength. At a wavelength of 10 cm (S-band), for example, attenuation and differential attenuation are almost negligible, but differential phase shift can be significant in large raindrops. No measurements of propagation effects due to the reorientation of hydrometeors by electric fields have been reported at 10 cm wavelength. At a wavelength of 1.8 cm (K_u-band), differential attenuation and differential phase shift are both significant in rain, and differential phase shift can be significant in ice crystals, even if the crystals are too small to yield measurable backscatter. Because the propagation effects are path-integrated, they can be detected even if the backscatter from hydrometeors is not detectable at all ranges in the path. As noted in subsection 3.1, the cross-covariance amplitude ratio (CCAR) is particularly useful for the

identification of these effects.

Measurements at the National Research Council of Canada from the mid-1970's to the early 1980's revealed several distinct categories of effects.[17, 29, 30, 31] The circular depolarization ratio (CDR) and the cross-correlation of the orthogonally polarized received signals were observed to change rapidly in conjunction with lightning strokes, either increasing, as shown in Figure 8, or decreasing, as shown in Figure 9, within about 2 sec. The cross-covariance amplitude ratio (CCAR) further reveals that the changes in the propagation medium were either between the radar and the first sampled range (Figure 8) or within the range increment sampled by the radar (Figure 9). In other cases, the orientation of the CCAR in the complex plane changed rapidly with the occurrence of lightning strokes, as shown in Figure 10, indicating sudden changes in the average orientation of hydrometeors in the propagation path. Periodic variations of propagation conditions due to electrical activity have also been observed on satellite communication links (e.g., McEwan et al.;[32] Watson et al.[33]).

4. OPPORTUNITIES

The fundamental concept of using a radar to observe effects of the electric field in clouds has been demonstrated. It has been suggested, but not demonstrated, that the electric field in clouds of water droplets can be deduced from radar measurements.[34] Such a capability would partially satisfy a critical need identified in a recent report by the Panel on Meteorological Support for Space Operations commissioned by the National Academy of Sciences.[35] Given the variability of hydrometeor characteristics in clouds and the very small magnitude of electrical effects on non-preciupitating droplets, it seems unlikely that quantitative estimates of the electric field can be derived from radar measurements, particularly in ice-phase or mixed-phase clouds. However, the qualitative identification of electrified clouds from radar measurements seems possible. The following subsections describe several lines of research that must be pursued in order to develop this capability. A related line of research, which may ultimately prove more fruitful, is to use polarization diversity radars to identify particular types of hydrometeors associated with electric charge separation.

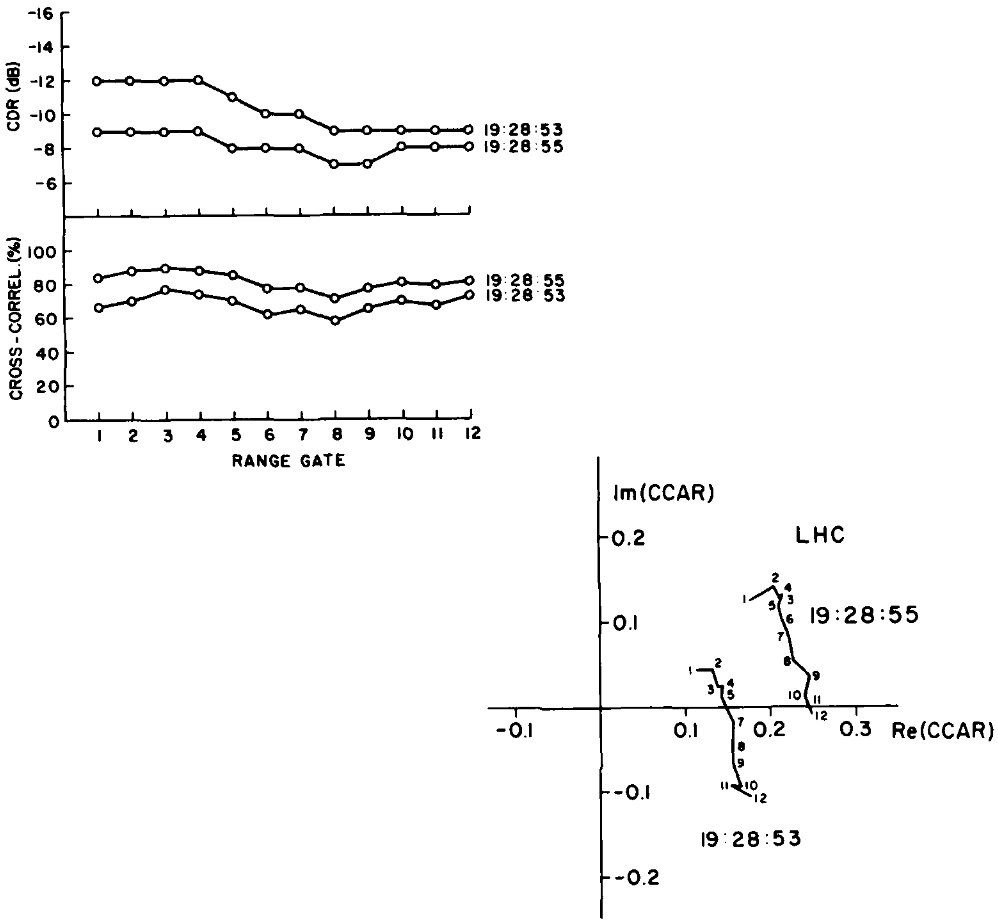

Figure 8. Effect of Electric Field on Radar Signal Propagation, 1. Observation was made in 1980 by 1.8 cm radar at the National Research Council of Canada in Ottawa. Range gate spacing is 0.5 km beginning at 43.2 km, elevation angle is 11.7°, and height is 8.7–9.8 km. *Upper panel:* Both the circular depolarization ratio (CDR) and the cross-correlation increase in all gates following a lightning event, while rangewise variations are nearly unchanged. *Lower panel:* Cross-covariance amplitude ratio (CCAR) reveals that change of propagation conditions occurred between the radar and the first gate; differential attenuation increased slightly and differential phase shift increased significantly. The trend of the CCAR from Gate 1 to Gate 12 is virtually unchanged, indicating no change of the electric field in that region (Copyright 1982 by the American Geophysical Union, reprinted with permission).[31]

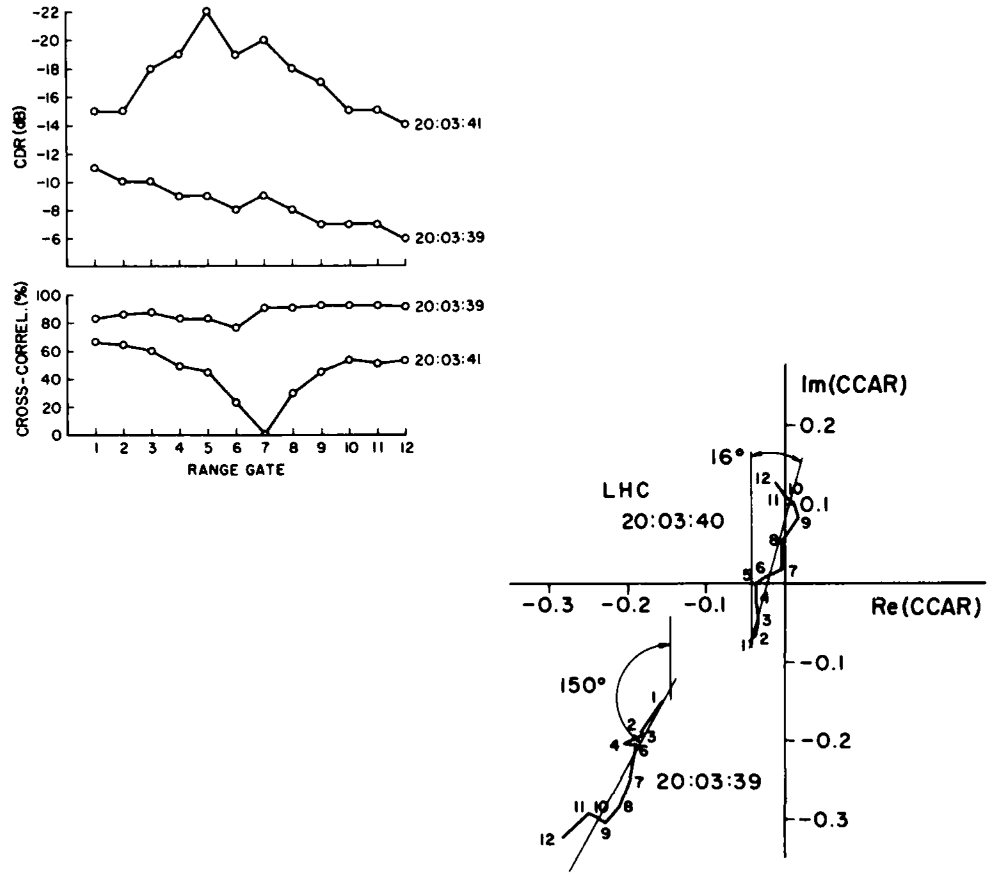

Figure 9. Effect of Electric Field on Radar Signal Propagation, 2. Observation was made in 1980 by 1.8 cm radar at the National Research Council of Canada in Ottawa. Range gate spacing is 0.5 km beginning at 39.0 km, elevation angle is 15.1°, and height is 10.2—11.6 km. *Upper panel:* Both the circular depolarization ratio (CDR) and the cross-correlation decrease in all gates following a lightning event, and rangewise variations are significantly different. *Lower panel:* Cross-covariance amplitude ratio (CCAR) reveals a slight change of propagation conditions between the radar and the first gate but a significant change between Gate 1 and Gate 12. The negative differential phase before the lightning event indicates that the major dimension of the particles was nearly vertical, possibly due to the electric field, whereas the positive differential phase shift after the event indicates that the major dimension of the particles was nearly horizontal (Copyright 1982 by the American Geophysical Union, reprinted with permission).[31]

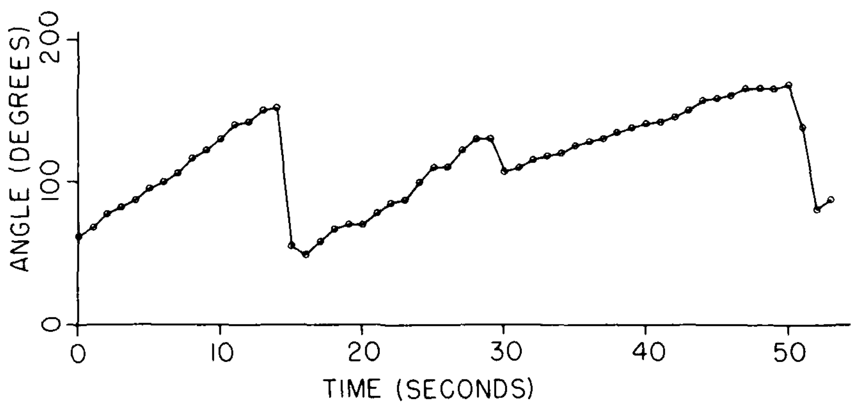

Figure 10. Effect of Electric Field on Radar Signal Propagation, 3. Observation was made in 1975 by 1.8 cm radar at the National Research Council of Canada in Ottawa. Range is 18.7 km, elevation angle is 21.3°, and height is 6.8 km. Ordinate is the orientation of the cross-covariance amplitude ratio (CCAR) in the complex plane, measured clockwise from the positive imaginary axis. It is approximately equal to twice the mean canting angle τ of the propagation medium. Values of 0°–90° correspond to positive differential phase shift and values of 90°–180° correspond to negative differential phase shift. Differential attenuation is largest, relative to differential phase shift, at 90° (Copyright 1979 by the Institute of Electrical and Electronics Engineers, reprinted with permission).[30]

This approach, coupled with laboratory research and numerical cloud simulation studies, could yield techniques of predicting cloud electrification from radar measurements.

4.1. Observations at Multiple Radar Wavelengths

The need to understand the effects of electric fields on hydrometeors of various types and sizes implies that observations should be made with radars of various wavelengths. Relatively short wavelengths, e.g., 0.86–3 cm, are most suitable for observations of small ice crystals. However, because propagation effects are relatively large at these wavelengths, simultaneous measurements by radars of longer wavelength will be necessary for the separation of effects manifested in backscatter and effects manifested in propagation. Observations of backscatter from rain or through rain must be made with radars of relatively long wavelength, e.g., 5–11 cm, if propagation effects are to be minimized. Because total attenuation and differential attenuation in rain are not negligible at 5 cm wavelength, a radar of 10–11 cm wavelength is most suitable for observation of backscatter effects through the full depth of a storm for comparison with observations by radars of shorter wavelengths.

With such measurements we can begin to answer a variety of questions about electrical processes in clouds. For example, do rapid changes of the electric field affect the orientation of small ice crystals only, or can the effects be observed in rain or mixed-phase media? Is the existence of a strong electric field or the occurrence of rapid changes of the electric field more readily deduced from propagation phenomena or from backscattering phenomena? What are the optimum wavelengths to detect electrical effects in different types of clouds or in different regions of a thunderstorm?

4.2. Observations of Temporal and Spatial Variability

In addition to the basic measurements described above, there must be attempts to document more fully the temporal and spatial variation of

hydrometeor orientation effects. Cyclical changes of measurable quantities at time scales of 10–20 sec, as depicted in Figures 4, 5, and 10, suggest the possibility of observing both temporal and spatial variations by repeated scanning of a radar beam through a small sector of azimuth or elevation angle. The details of the rapid changes will be lost when the radar beam is scanned, but repeated scanning of a region no more than a few kilometers in horizontal or vertical extent with a scan cycle time of a few seconds should reveal aspects of the spatial distribution of the electric field and the ways in which discharges change the field. The resulting time resolution of a few seconds should be sufficient to reveal the general characteristics of the variability depicted in Figures 4, 5, and 10. The value of such observations in ice-phase propagation and backscattering media is evident from the observations cited in this report. Similar techniques should be used to investigate the effects of changing electric fields on water drops, both in unglaciated clouds and in rain.

4.3. Coordinated Multi-sensor Measurements

A fundamental goal of any multi-sensor measurements, either multi-radar measurements or coordinated measurements by radars and other sensors, is to increase the reliability or accuracy of the interpretation of radar measurements. Multi-sensor measurements may be aimed at outright verification of the radar measurements, e.g., by coordinated measurements of electrical quantities or hydrometeor characteristics by ground-based or airborne instruments. Multiple measurements by remote sensors can be designed to increase confidence in the results through self-consistent interpretation. Of greatest importance to understanding of atmospheric electrical processes is the documentation of electric fields and electric discharges in clouds in conjunction with radar measurements. To some extent this can be done with ground-based instrumentation, e.g., field mills and lightning location systems. More precise interpretation of the radar measurements can be made if the electric field is measured by airborne instrumentation. Airborne measurements are of particular importance to the interpretation of radar measurements of clouds that are only moderately electrified and of high-altitude clouds, because the electric field

aloft can not always be inferred reliably from measurements of the electric field near the surface of the earth.

The preceding discussion of radar measurements in subsection 4.2 noted that detailed measurements of temporal and spatial variability tend to be mutually exclusive. One solution to this dilemma is the use of two radars, one to observe an electrically active region with fixed beam and the other to scan a small adjoining sector. Two or more radars, scanning different portions of an anvil, could also be used to identify effects of the electric field as it evolves in space and time. Such measurements might be made with radars of similar wavelength, to assure that the propagation and backscatter characteristics are similar, or of different wavelengths, to meet some of the objectives described in subsection 4.1 above. The full specification of a multi-sensor measurement program is well beyond the scope of this report. The present comments are intended to show that such a program is technically feasible and is likely to be scientifically productive.

In emphasizing the measurement of the electric field, we should not neglect the need to understand better the role of hydrometeors in cloud electrification. The use of polarization diversity radars to identify certain types of hydrometeors, e.g., raindrops, ice crystals, graupel, and hail, has been demonstrated in recent years,[36] although there are uncertainties and ambiguities that require improved verification of the radar measurements. Measurements of hydrometeor characteristics and electric fields by airborne instruments in coordination with polarization diversity radar measurements will yield increased understanding of the microphysical conditions associated with electric charge separation and transport. As such measurements lead to the improvement of numerical cloud models it may become possible to use radar measurements to identify or predict electrical conditions in clouds.

5. CONCLUSION

Echoes from lightning channels can be detected by radars with wavelengths typically used for meteorological measurements, either in linear copolarized signals with wavelengths longer than about 5 cm or in linear

cross-polarized signals. The orientation of the ionized channels can be estimated from the polarization differential reflectivity, which is derived from measurements with alternating transmission of horizontally and vertically polarized signals. It should be possible to derive the apparent orientation of the ionized channels from measurements by radars with dual-channel receivers, but this has not yet been attempted.

Variations in the orientation state of hydrometeors under the influence of a varying electric field have been observed by radar. These observations support the hypothesis that radar measurements can provide valuable information about the evolution of the electric field in clouds. Past observations have been made with single radars operating with fixed beams and with few or no supporting electrical data. Existing polarimetric radars operating at wavelengths of 8.6 mm, 3 cm, 5 cm, and 11 cm can be used with electric field and lightning detection equipment to expand knowledge of atmospheric electrical processes and to provide needed information in support of aircraft and spacecraft operations.

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